Virtual Solar Cell Tester System Based on Modified Interval Type-2 Fuzzy Logic Controller

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Abstract: ***The most fundamental of solar cell characterisation techniques is the measurement of cell efficiency. Standardised testing allows the comparison of devices manufactured at different companies and laboratories with different technologies to be compared. This paper presents a new design of solar cell testers for monocrystalline, polycrystalline, cadmium telluride (CdTe), and copper indium diselenide (CIS) cells. Each cell is tested for efficiency and categorized accordingly into four groups (A to D). A Virtual Reality (VR) model was built to simulate the system, keeping in mind real world constraints. Two photoelectric sensors were used to make detections for both the testing process and the robot movement. A handling robot with vacuum end-effectors was designed based a Modified Interval Type-2 Fuzzy Logic Controller (MIT2FLC) and command line programming for construction, editing, and simulation of the MIT2FLC for control of movement for solar cell and then distributed the cells according to the categories of test for efficiency. The MIT2FLC guides the trajectory of the robot according to the results of the efficiency testing. It was seen that the system worked very well, with the testing process and the robot movement interacting smoothly. The robot trajectory was seen to be highly accurate, and the pick and place operations were done with great precision.***

Keywords: Handling robot, Solar cell tester, Virtual reality, a Modified Interval Type-2 Fuzzy Logic Controller (MIT2FLC).

I. INTRODUCTION

Solar cell, technical name Photovoltaic (PV), is the booming technology which converts sunlight (Including visible or ultra violet radiation) into electricity. Due to today's growing demand for green energy, the solar cell is increasingly used in many areas, such as buildings, infrastructure and even mobile devices, as these industries become more eco-conscious. While PV devices absorb the solar irradiance and convert it into energy, the Keysight Technologies, Inc. I-V tester solution can measure the performance of various PV devices such as Silicon/ Thinfilm/ multi-junction in different power ranges. This could then be integrated with solar simulators for in-house tests. It is also suitable as a standalone for outdoor testing. [1- 6]:

A cheap alternative to generating solar electric power are Silicon-Film solar cells. The production systems of Silicon-Film use a continuous in-line process to produce polycrystalline silicon sheets. The Apex sheet growth process has continuously progressed and after five design generations, one sheet can give an annual yield of over 15 MW of 200-mm wide polycrystalline silicon sheet, which is used to make large-area APx-8 solar cells. These cells generate over 4 W each and have edge dimensions of 208mm x 208mm.

Parallel process systems are often used to increase the volume of solar cells manufactured. However, with modern large-area Apex sheet generation approaches and the development of solar cell process tools, single-thread process systems can be used to design large volume production lines for solar cells [7-11].

Recent years have seen a dramatic increase in the solar industry, due to which solar cell and module test solutions are widely sought after. The solar cell modules are generally of two types: comprehensive turnkey solutions and test-system building blocks that must be assembled. The former are easy to set up but expensive. Furthermore, the technology used in the turn-key solution is likely to become outdated quickly, thus requiring an upgrade. With building blocks though, the system is more reasonably priced and is easily modified when required. If there is a need to upgrade to a higher current range or accuracy, only one relevant block would need to be replaced. Also, sets of blocks that are useful for a variety of platforms can be standardized and reused [11-14].

This paper contain introduction, design the VR model for solar cell tester, the design and analysis of a handling robot to transfer solar cells from the surface of the conveyer to four main boxes is proposed, with special consideration of the percentage of efficiency, Structure of a Modified Interval Type-2 Fuzzy (MIT2-FC) Controller, simulation results and conclusion.

II. VIRTUAL TESTER MODEL

The robot is designed in two main phases. In the first phase, the robot is designed in a VR environment and the controller performance is tested in simulation. VRLM software was used for the design. The 'classical objects' feature in the software was used to create the preliminary design. The objects were then redrawn using the indexed-face option to obtain the advanced design. Figure 1 illustrates the design of the solar cell tester with robot arm in VR.

To design and simulate the movement of the robot, a trajectory was set for the robot after a number of trials. The trajectory advances in three stages (Figure 3): first, the cell is handled and moved vertically up to a specified point; second, the cell is moved horizontally to a certain point and finally the cell is lowered vertically to box A, B, C or D. The robot needs to complete this trajectory in 30 sec. Due to the thin construction of the solar cell and light weight (20 gm), it is quite difficult to pick the cells from the conveyer.

Manuscript Received on April 2015.

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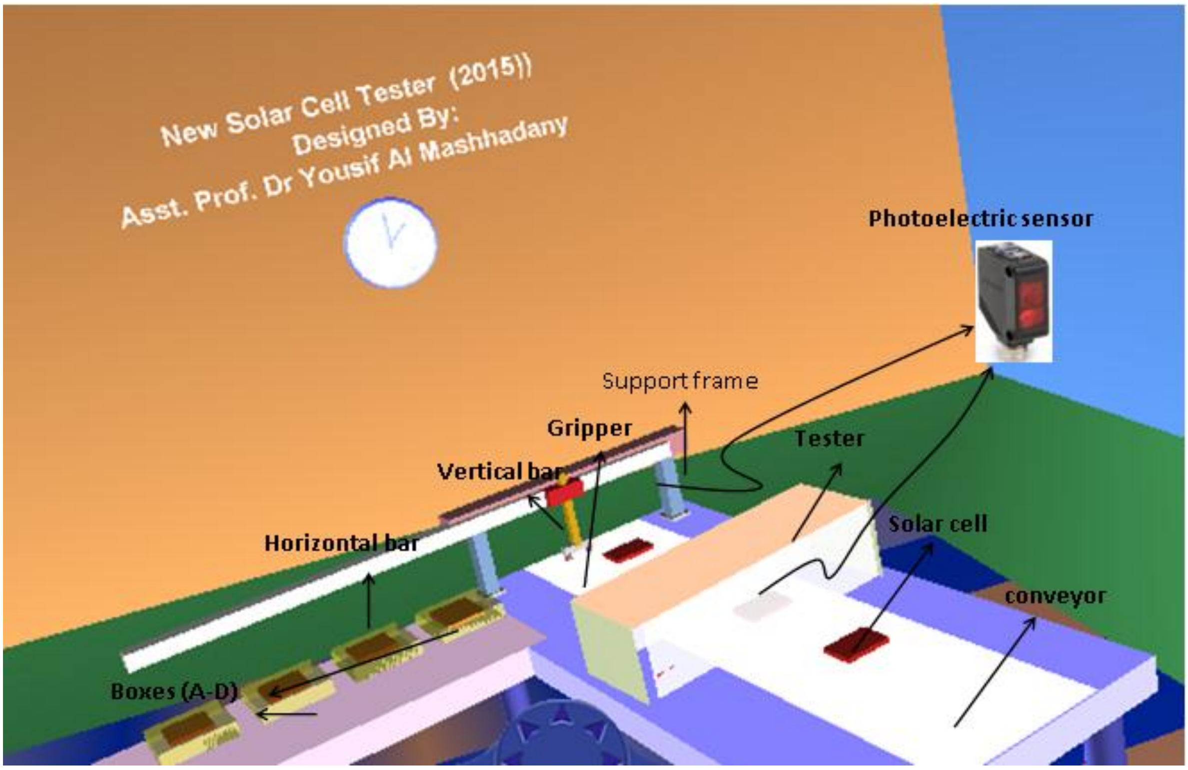

Fig. 1. Design Virtual Reality model for solar cell tester

To ensure that each part of the robot was best suited to its job, a number of robot designs were tested in simulation. For picking the cells from the conveyer (which requires accurately capturing them through the conveyer trajectory) and placing the cells in the appropriate box, the vacuum technique was used. Two vacuum grippers were used for this purpose.

III. CONTROLLER DESIGN

A. Modelling of an Interval T-2 Fuzzy Inference System

Human knowledge is expressed as a set of fuzzy rules, which are basically of the form IF <Antecedent> THEN <Consequent> and express a fuzzy relationship or proposition. In FL, the reasoning is imprecise and approximated; one rule is enough inference for a conclusion, even if the antecedent does not fully comply. Basic inference methods between rules and inference laws are Generalised Modus Ponens (GMP) and Generalised Modus Tollens (GMT), each representing the extensions or generalisations of classic reasoning. The GMP inference method is known as direct reasoning and is represented as

Rule: *IF x is A then y is B* ☞☞ *Fact x is A'* ☞☞☞

Conclusion: y is B

with A, A', B, and B' being fuzzy sets of any type. This relationship is expressed as $B' = A' \circ (A \rightarrow B)$. Figure 2 exemplifies Interval T-2 direct reasoning with Interval T-2 Fuzzy Inputs. An Inference Fuzzy System is a rule-based system that uses FL instead of the Boolean logic of data analysis. Its basic structure has four components (see Fig. 2) [15-21].

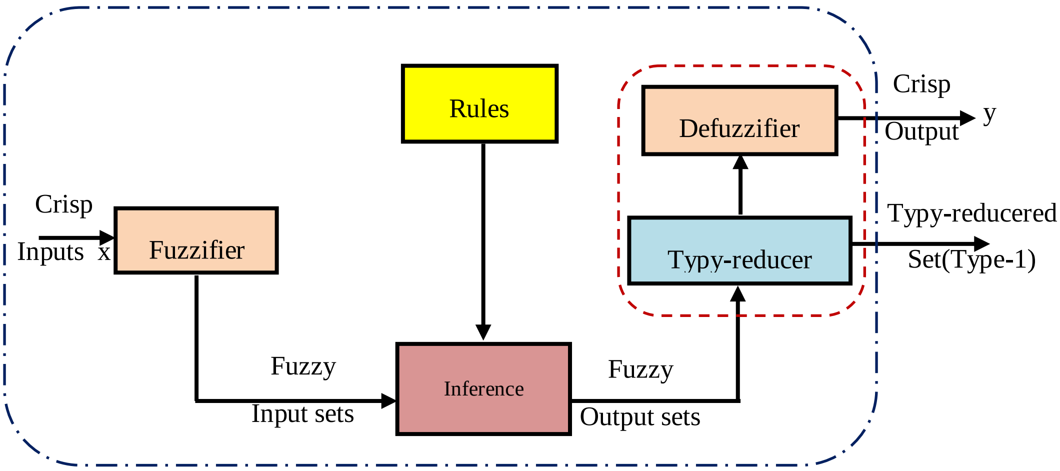

Figure 2: Structure of a T-2 inference fuzzy system

Characterising a T-2 fuzzy set is not as easy as characterising a type-1 fuzzy set. A T-2 fuzzy set, denoted by $\tilde{A}$, is characterised by a T-2 MF $\mu_{A^\sim}(s,u)$ where $x \in X$ and $u \in J_x \subseteq [0,1]$, i.e.:

$$A^\sim = \{((x,u), \mu_{A^\sim}(x,u)) \mid \forall u \in J_x \subseteq [0,1]\}$$

(7)

in which $0 \le \mu_{A^\sim}(x,u) \le 1$. $A^\sim$ can also be expressed as

$$A^\sim = \int_{x\in X} \int_{u\in J_x} \frac{\mu_{A^\sim}(x,u)}{(x,u)} J_x \subseteq [0,1]$$

(8)

with $\iint$ denoting union over all admissible *x* and *u*.

In (1), $\mu_{A^\sim}(x',u')(x' \in X', u' \in J_{x'})$ is secondary grade. Imagine blurring the type-1 MF depicted in Figure 3(a) by shifting the points on the triangle either to the left or to the right but maybe not by the same amounts. Then, at a specific value of *x*, say *x'*, there is no longer a single value for the MF; instead, the MF takes on values wherever the vertical line intersects the blurred. These values do not need to be weighted the same; hence, we can assign an amplitude distribution to all of these points, after which, for all *x* ∈ *X*, a three-dimensional MF is created, a T-2 MF that characterises a T-2 fuzzy set. We can re-express $A^\sim$ in a vertical slice as [20-22]

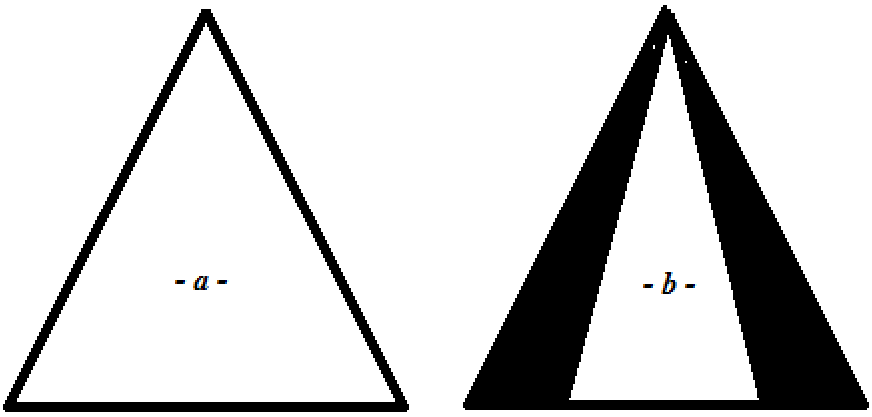

Fig. 3: (a) Type-1 MF, (b) Blurry type-1 MF

$$A^\sim = \int_{x\in X} \frac{\mu_{A^\sim}(x)}{x} \int_{x\in X} \frac{\left[\int_{u\in J_x} f_x(u)/u\right]}{x} J_x \subseteq [0,1] \qquad (9)$$

The domain of a secondary MF is called the primary membership of x, where $J_x \subseteq [0,1] \forall u \in X$. If X and J_x are both discrete, then Equation (10) can be expressed as

$$A^\sim = \sum_{x\in X} \frac{\left[\sum_{u\in J_x} f_x(u)/u\right]}{x} = \sum_{i=1}^{N} \frac{\left[\sum_{u\in J_{x_i}} f_{x_i}(u)/u\right]}{x_i}$$
$$= \frac{\left[\sum_{K=1}^{M_1} fx_1(u_{1k})/u_{1k}\right]}{x_1} + \ldots + \frac{\left[\sum_{K=1}^{M_N} fx_N(u_{Nk})/u_{Nk}\right]}{x_N} \qquad (10)$$

Uncertainty $A^\sim$ in the primary memberships of a T-2 fuzzy set consists of a bounded region (FOU) (Karnik & Mendel, 2000). It unifies all of the primary memberships:

$$FOU(A^\sim) = \underset{x\in X}{U} J_x$$

(11)

*The concept of F*OU, associated with the concepts of lower and upper MFs, lets us easily characterise T-2 fuzzy sets. The FOU models uncertainties in the shape and position of a type-1 fuzzy set. Fig. 8 illustrates a T-2 fuzzy MF with its FOU (shaded). T-2 Gaussian MF is obtained by blurring a type-1 Gaussian MF with mean m_k and standard deviation σ_k. Consider the case of a Gaussian primary MF with a fixed mean m_k and an uncertain standard deviation that takes on values in $[\sigma_{k1}, \sigma_{k2}]$, i.e.,

$$\mu_A(x) = \exp\left[-\frac{1}{2}\left(\frac{x-m_k}{\sigma_k}\right)^2\right]; \quad \sigma_k \in [\sigma_{k1}, \sigma_{k2}]$$

(12)

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Different membership curves for each of the two σ_k (σ_{k1}, σ_{k2}) values can be calculated. The uniform shading for the FOU again denotes interval sets for secondary MFs and represents the entire interval T-2 fuzzy set $\mu_A(x, u)$. The FOU can be described in terms of upper and lower MFs (see Figure 4). An upper MF and a lower MF are two type-1 MFs that are bounds for the FOU of a T-2 fuzzy set $\tilde{A}$. The upper MF is associated with the upper bound of the FOU ($\tilde{A}$) and is denoted $\overline{\mu}_{\tilde{A}}(x), \forall_x \in X$.

$$\overline{\mu}_{\tilde{A}}(x) \equiv \overline{FOU(\tilde{A})} \quad \forall_x \in X \quad and \quad \underline{\mu}_{\tilde{A}}(x) \equiv \overline{FOU(\tilde{A})} \quad \forall_x \in X \tag{13}$$

Because the domain of a secondary MF has been constrained in (1.0) to be contained in [0, 1], lower and upper MFs always exist. Note that J_x is an interval set:

$$J_x = \{(x,u) : u \in [\underline{\mu}_{\tilde{A}}(x), \overline{\mu}_{\tilde{A}}(x)]\} \tag{14}$$

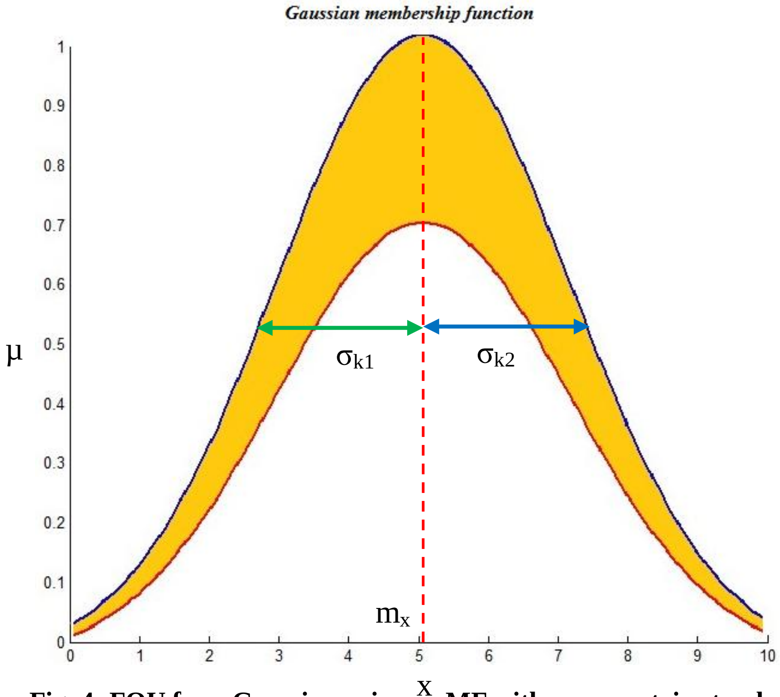

Fig. 4: FOU for a Gaussian primary MF with an uncertain standard deviation

In a general T-2 FLS, the fuzzifier maps crisp numbers into fuzzy sets. It is necessary to activate rules that are expressed in terms of linguistic variables, with fuzzy sets associated with them. The inference-engine maps input fuzzy sets into output fuzzy sets. In many applications of an FLS, a crisp number must be obtained at fuzzy sets output, which is accomplished by the output processor. The output processor of a type-1 FLS is just a defuzzifier, while the Out-processor of a T-2 FLS contains two components: the first maps a T-2 fuzzy set into a type-1 fuzzy set, and the second performs defuzzification on the latter set. In type-1 FLS, we generally have IF–THEN rules in the form of Equation (15):

$$R_1: \; IF \;\; x_1 \;\; is \;\; F_1^l \;\; and \;\; ...... \;\; and \;\; x_p \;\; is \;\; F_1^l, \;\; THEN \;\; y \;\; is \;\; \tilde{G}^1; \qquad l = 1,.......M \tag{15}$$

The distinction between type-1 and T-2 rules is associated with the nature of the MFs; the structure of the rules remains exactly the same in the T-2 case, but all of the sets involved are T-2. We can consider a T-2 FLS having p inputs $x_1 \in X_1$, . . ., $x_p \in X_p$ and one output $y \in Y$; assuming there are M rules, the lth rule of T-2 FLS has this form in Equation (16):

$$R_1: \; IF \;\; x_1 \;\; is \;\; \tilde{F}_1^l \;\; and \;\; ...... \;\; and \;\; x_p \;\; is \;\; \tilde{F}_p^l, \;\; THEN \;\; y \;\; is \;\; \tilde{G}^1; \qquad l = 1,.......M \tag{16}$$

This rule represents a T-2 relation between the input space and the output space of T-2 FLS. When arbitrary T-2 fuzzy sets are used, a T-2 FLS is computationally prohibitive. On the other hand, when all T-2 fuzzy sets are modelled as interval sets, an IT-2 FLS that is usable is obtained [23,24]. In this case, input–output domains are characterised by IT-2 sets, with the membership grades (secondary) of all elements in the FOU being unity. In addition, the fuzzifier converts the input signals of the FLS into fuzzy singletons. The inference engine then matches the fuzzy singletons with the fuzzy rules in the rule base; at first, it produces a firing set, which is then used to produce an output consequent set MF for each firing rule, which can then be used to produce an MF for all (combined) firing rules. The type-reducer leads to a type-reduced set that provides an interval of uncertainty for the output of a T-2 FLS. Whatever the type-reduction method, the type-reduced set of an interval T-2 FLS is an interval type-1 set, and its two end-points can be computed by using an exact iterative method developed following extensive research. Because the type-reduced set is an interval set, its defuzzified value is simply the average value of its two end-points [24,25].

B. Structure of a Modified Interval Type-2 Fuzzy (MIT2-FC) Controller

Unlike conventional control, which is based on a plant's mathematical model, FLC usually embeds the intuition

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and experience of a human operator and sometimes those of designers and researchers. When controlling a plant, a skilled human operator's aim is to manipulate the process input (i.e., controller output) based on *e* and Δ*e* as fast as possible and with the least error. The controlled variable of fuzzy controller is u(t). The MFs of the input and output variables must be considered once the fuzzy controller inputs and outputs are chosen. This paper defines all MFs for the conventional fuzzy controller inputs (*e* and Δ*e*) and the controller output on a common normalised domain [-1, 1],. Symmetric triangles (except the two MFs at the extreme ends) were used, with an equal base and 50% overlap with the neighbouring MFs. This choice is the most natural and unbiased for MFs. Figure 5 shows the seven MFs: MN (Most Negative), NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero Error), PS (Positive Small), MP (Most Positive), PM (Positive Medium), and PB (Positive Big). The rule base was designed next. If the inputs have 9 MFs, the corresponding rules are 9^2=81. The design process enables the actual control input voltage for the main fuzzy controller (ANFIC) to be written as:

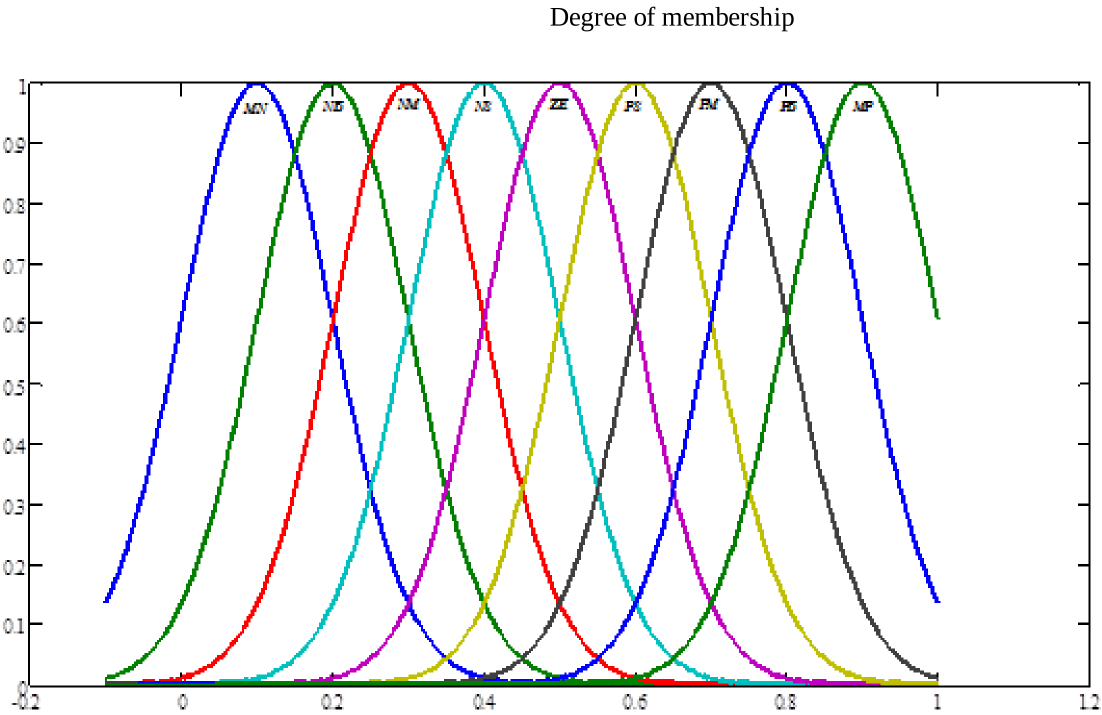

Fig. 5. MFs for *e* , Δ*e* and Δ*u*.

$$u(k+1) = u(k) + \Delta u(k)$$
(17)

Equation (17) denotes the sampling instant as k and the incremental change in controller output as *Δu(k)*. MF in interval T-2 FLS is the FOU area, which is limited by two type-1 MFs: the Upper MF (UMF) and Lower MF (LMF). There are two inputs and one output, and each input/output variable has the same seven linguistic variables. The FIS of this paper was the Sugeno method (also called the Max-Min method). Operation on the interval T-2 fuzzy set was identical to that on a type-1 fuzzy set. However, in the interval T-2 fuzzy system, fuzzy operation is on type-1 MFs, limiting the FOU, LMF, and UMF to produce the firing strengths.

IV. SIMULATION RESULT

The simulation of the design was achieved by using Matlab Ver. 2014a with VR environment to implement the movement of system by interfacing with Matlab/Simulink.

Figure 6 presents the simulation results by using VR display of the control signal for each part of the solar cell tester.

The operation of the cell testing system commences with the movement of the solar cell upon the conveyer. Figure 7 shows the movement signal for three cells. As is evident from the signal, the sequence repeats after every 50 sec. After 10 sec, the first cell arrives at the tester and the flash tester turns on and off for 5 seconds each. The sequence is then repeated for the second cell (as is clear from the tester flash signal in scope (c) of Figure 7. After 25 sec, the first cell arrives at the capture point to be picked by the gripper of the robot. The down-up signal for the gripper is shown in scope (b) in Figure 7. The horizontal movement of the robot depends on the efficiency of the cell calculated by the tester. Depending on the box number that the cell is to be placed in, the amplitude of the horizontal movement signal (scope (a) of Figure 7) is limited. The duration of one cycle, from passing the entry point to being placed in a box is 50 sec. The output of the virtual model that simulates the movement is shown in Figure 7.

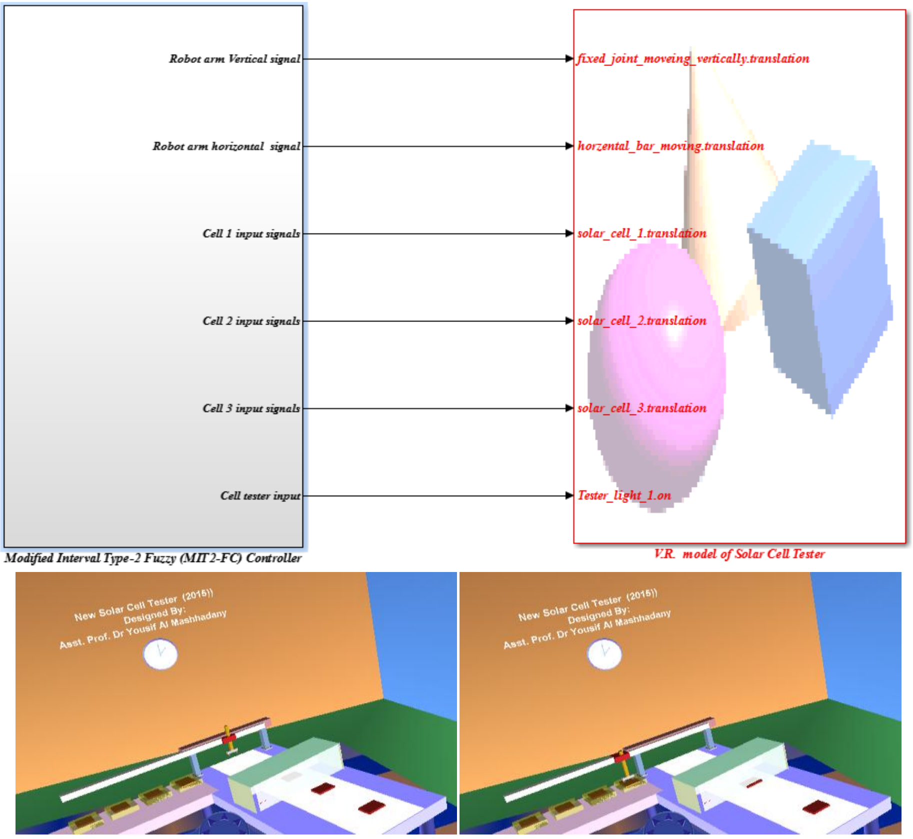

Fig. 6. Implement solar cell tester in V.R. model.

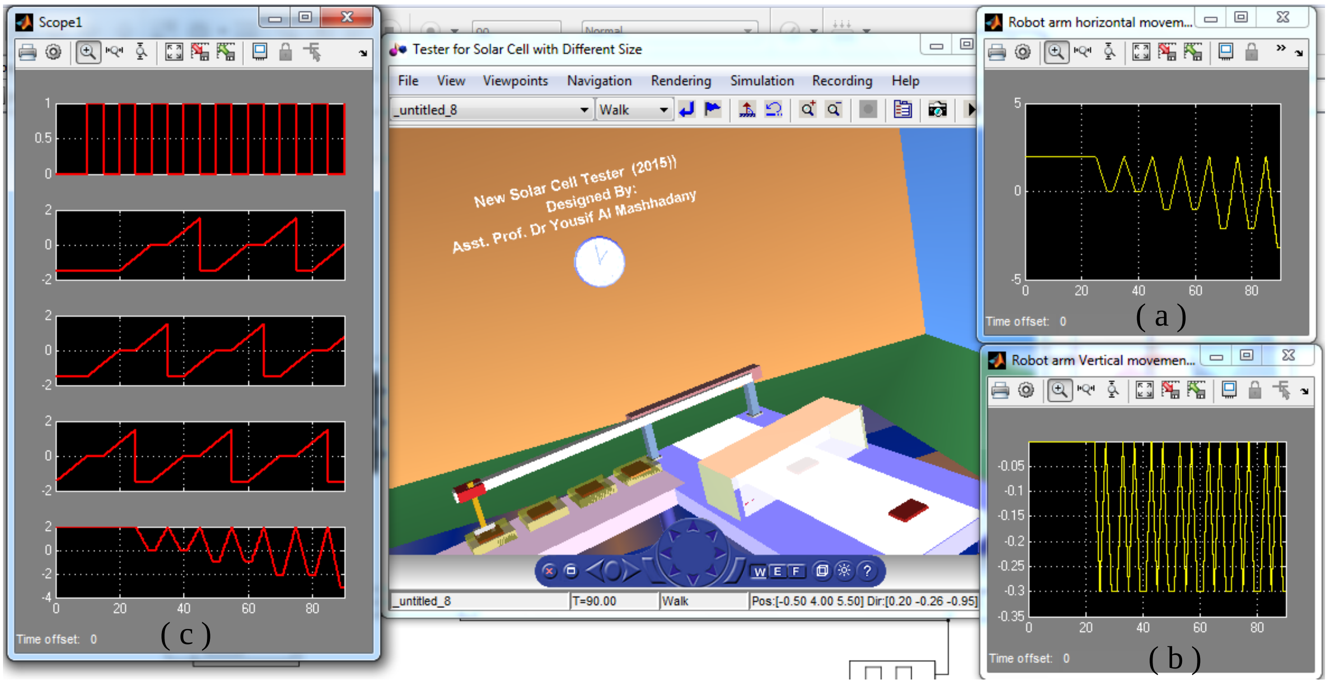

Figure 7. Tester flash signal, Solar cells movement signal and Robot arm horizontal movement signal.

V. CONCLUSION

The design of virtual solar cell tester according to practical testing values based on MIT2-FC is very accurate and it has many advantages over the traditional tester and from the simulation results can concluded that:

- It has ability to apply testing process twist faster than traditional tester, because the reaction time is less than half value.
- It has ability to deal with many types at the same time because it has ability to memorized the data base and apply the procedures of testing with any type of cell randomly.
- It needs very fasting handling robot therefore

apply the design of handling robot based on translational motion of robot arm.

- The simulation results improved the design to apply as practical model based upon microcontroller to apply the MIT2-FC card.

ACKNOWLEDGEMENT

Special thanks from author to Ishik University for supporting this work.

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